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Gridshell structures in glass fibre reinforced polymers

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ABSTRACT

Applications in which composite materials are used as bearing structural elements are rare and generally copy structural solutions that have been optimized for steel for years. Unfortunately these materials have very different properties, therefore specific construction methods and specific structural forms have to be invented for composite materials. Gridshell structures may be one of those. So, after a brief history of gridshells, a demonstration with the Ashby's method that glass fibre reinforced polymers are an alternative for this kind of structure is shown. An original experimental test for the identification of the parameters of the short and long time behaviours of bent pultruded tubes is then detailed. Afterwards a scale one prototype of composite gridshell is presented and loaded. Results of the experimental tests are compared to numerical results of a non-linear analysis done with the dynamic relaxation method. The authors then concluded on the feasibility of such composite gridshells and on their potential for future development.

1. Introduction

Applications in which composite materials are used as bearing structural elements are rare and generally copy structural types that have been optimized for steel for years. Of course composites are more and more involved in civil engineering and many structures are built today all over the world; numerous cable stayed bridges with composite cables as well as numerous footbridges and road bridges with composite decks and longitudinal beams are now in service especially in Japan and North America. A free form composite sandwich roof was also build in Tel Aviv for the Yitzhak Rabin centre in 2004 [1]. Nevertheless main reasons for this success are often not the mechanical properties of composites but rather their low density and their easy maintenance. Indeed for bridges or roof structures like I-beam, box girder or trusses, the dimensioning factor is the bending stiffness which is much lower for composites than for steel. Composites constructions have therefore more heavy and clumsily appearance despite the lightness of the material. Moreover for the earliest bridges, gluing was not considered as a reliable enough technique and this overdimensioning of the beam was accentuated by the use of connections with holes and bolts that create stress concentration.

Innovation by imitation is a common procedure when a new material appears but, to be really efficient, specific forms and specific construction methods for composites have to be invented, which means:

- to take benefit of the high elastic strain and high limit stress of the fibres;
- to minimise and to simplify connections to reduce stress concentrations and costs; and
- to use as much as possible prefabricated elements to increase quality and reduce costs.

For several years, the authors are developing Taylor-made applications in this sense. Two different types of structures have been mainly studied. The first one is a 40 m footbridge principle with an innovating bowstring type. The particularity of the tubular arches of the proposed footbridge is that they are obtained by elastic bending of pipes. This provides a cheap way to form arches on the one hand and, on the other hand, a method to store elastic energy and to prestress cables and retainers [2]. The second type of structure is an innovative gridshell structure and will be discussed in this paper.

The concept of gridshell (or gridshell) commonly describes a structure with the shape and strength of a double-curved shell, but made of a grid instead of a solid surface. This kind of roofing structures can cross large span with very few material. They can be made of many kinds of material – steel, aluminium, wood or even cardboard tubes... Generally, the metallic structures are made of short straight elements defining a facet geometry which is covered by plane glass panels. The complexity of this geometry

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requires the development of many clever and expensive assemblies [3]. To mitigate this disadvantage, a very specific erection process was developed in the sixties by Frei Otto and the *Institut für Leichte Flächentragwerke* in Stuttgart [4]. It uses the ability of slender components to be bent, to build a double curved grid starting from a flat grid. Long continuous beams are first assembled on the ground in two orthogonal directions and pinned between them at every connection in order to form a grid with no plane shear rigidity. This property will allow large out-of-plane deformations of the grid by elastic bending until the desired form is obtained. It is then fixed to its boundary conditions and rigidified by bracing through diagonal cables or a third direction of beams.

Few structures have been built following this erection procedure. Some experimental prototypes spanning less than 10 m have been realised by Frei Otto in the sixties and early seventies with slender rebars or wood pieces [4]. But the potential of gridshells was really revealed in 1975 when the multi-purpose hall in Mannheim was built spanning over 60 m [5]. This structure was astonishing not only by its extremely light and transparent wooden roof but also by its free futuristic shape which seamed promising for many architects of this revolutionary period. Nevertheless it did not become widespread and, during almost 25 years, no major gridshell was achieved.

In the last 10 years with the evolution of numerical tools for structural design and especially the development of software based on the dynamic relaxation algorithm, the calculation of the form and the erecting process became easier and a few wooden gridshells have been realised in the United Kingdom, among which the new carpenter hall of the Weald and Downland Museum (E. Cullinan, architect and Buro Happold, structural engineers) [6]. For this structure, a special finger jointing machine and special polyurethane glue working at a pressure of 40 atmospheres was used to joint the wood pieces after the removal of defective sections (like knots). This technique limits timber waste and maximises the quality of the beams but leads to an "artificialization" of the material and to the multiplication of costly treatments of the wood. Thus, one could ask why not substitute wood by another material which will have all the industrial qualities required.

In 2000, the Japanese architect Shigeru Ban (with help of Frei Otto and Buro Happold engineering) made an attempt in this direction in designing a totally recyclable gridshell made of cardboard covered with coated paper for the Japanese pavilion of the Hanover Word Exhibition [7]. Unfortunately the proof engineer hired by the city of Hanover stood distrustful, even if the material of the roof had already cleared the fire standard tests. He imposed this temporary structure to be designed as a permanent one, forcing the design team to add reinforcing wooden arches which are prejudicial from the viewpoint of structural purity [8]. In spite of everything, the public and the architectural critics loved the pavilion, confirming the constant interest for the shape created by gridshells. Nevertheless the authors still think that the right material for gridshell is still to be found and will try to demonstrate in this paper the relevance of composite materials, and especially glass fibre reinforced polymers (GFRP) for gridshell structures.

The article will thus be presented as follow. In the first section, the interest of composites for this kind of application is explained with help of the Ashby's method. Section 3 is then concerned with the preliminary tests on the material to be used for the prototype and with the determination of the short and long time behaviours of bent composites. Then Section 4 describes the calculation and the construction of a prototype of gridshell in GFRP and details the experimental procedure used for the study of its behaviour under loading. In the last section, the results of the experiments are analysed and compared with a numerical analysis based on the dynamic relaxation method. A brief discussion concludes the paper on the feasibility of composite gridshells and shows a recent realisation including a textile roof.

2. Composite materials and gridshells

As previously mentioned, most of the gridshell structures have been made with wood as it is the only traditional building material that can be elastically bent without breaking. However looking at other industrial fields (sport and leisure, nautical...), it can be noticed that every time high strength and high deformability are required, composite materials are replacing wood (ship mast, skis, racket...). To study accurately the question of the best material for gridshells, the authors have adopted the method proposed by Ashby [9]. In this method, one first defines indicators which characterize the constrains of the object to be designed. In this case, one needs to have a material with:

- high elastic limit strain to fit with the construction process (given by the ratio elastic limit stress over Young modulus);
- high Young modulus to confer to the gridshell its final stiffness after bracing;
- low ratio "Young modulus over price per volume unit" (as it is important to know what stiffness one can get with one volume unit);
- high tenacity because the material has to be handled easily by workers on site;
- high resistance to fire or aggressive atmosphere; and
- high environmental properties such as the ratio "energetic cost per volume unit" or "amount of toxic products used during fabrication process".

In total, seven parameters have been defined and compared for all the materials available for the today engineers [10].

The paper will focus here on the first two points (elastic limit strain and Young modulus), but the fire resistance must be highlighted as it is a natural concern of engineers and contractors. Fire requirements vary greatly according to use and national legislation, so that specific requirements for every specific structure should always be obtained. It is possible, in many cases, to adjust the matrix (phenolic resin for example) and/or to add fire-retardants to fulfil these requirements. To assess this fact, consider that aeronautic and naval industries, which are drastically concerned by fire aspects, include many composite structural elements in their structures or that, in some applications, composite materials are even used as a protection shield for the metallic part of a structure. Actually, a composite material, like the pultruded pipe used in this study, burns slowly like wood and does not collapse like metallic pipes.

So, turning back to elastic limit strain and Young modulus, and considering Fig. 1, one can see a typical log–log graph used in Ashby's method. The *X*-axis represents the elastic limit stress in MPa and the *Y*-axis the Young modulus in MPa. The oblique line I_2 on this graph represents the limit between materials that have an elastic limit strain higher than woods with high strength such as oak or fir (the woods chosen for the construction of existing gridshells). The horizontal line I_2 represents the limit between materials that have a Young modulus higher than wood. Hence the materials isolated in the corner between the two lines (titanium, CFRP, GFRP and technical ceramics) will have better mechanical properties than wood and their application for gridshell structures will thus be interesting to study. It appears clearly that traditional materials (like iron or steel or concrete) exhibit much lower deformability than wood, confirming the logical choice made for the gridshells until then.

To choose between the remaining materials (wood, titanium, CFRP, GFRP, and ceramics), several comparisons of the seven